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Analytical Investigation of the Influence of Soil on Tanks for Seismic Analysis of Nuclear Power Plant

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SUMMARY

When seismically designing equipment, such as ground supported tanks of nuclear power plants, the free field response spectra are normally applied to a model having a fixed base. The consideration of soil structure interaction, which routinely has been applied to nuclear power plant building structures constructed on the soil surface, has not normally been applied to equipment.

In this study, the effect of soil structure interaction on seismic response of tanks will be evaluated as a function of soil surface stiffness and depth using the calculated soil stiffness equations developed by Dr. H. Tajimi. The authors investigated the influence of the soil properties and composition represented as soil springs which depend on the soil conditions (shear modulus, density, Poisson's ratio) and the depth of soil surface.

The results of this study are presented in the form of graphs which may be used to identify the range of soil parameters which have a significant effect on the seismic response of typical nuclear power plant tanks.

In this paper, a typical example to express the influence of the soil surface for seismic response and vibrational characteristics is presented.

1. INTRODUCTION

When designing ground supported vertical storage tanks for earthquake resistance, it may be important to consider the tank and soil interaction. To investigate this effect, a simple foundation profile of two layers was considered; one representing the surface layer of soil and the other the base rock. Both layers in the soil profile combine to produce resistance, which in this simplified evaluation are modeled as a spring for each degree of freedom. The relative stiffnesses of the soil layers are computed using the formulae developed by Dr. H. Tajimi[1]. In these formulae the stiffness ratio and the dimensionless depth of the soil profile are the controlling parameters. The calculated coefficient factors(CF) as developed and defined in Section 2 of this paper are shown in Table 1 and Figure 1. The relation of effective stiffness ratio to profile depth and to soil stiffness are shown in Figures 2 and 3.

The ground supported tank shown in Figure 4, was modeled as a stick with a diameter to height ratio that is common to many ground supported tanks at nuclear power plant facilities. The water in the tank was modeled by using lumped masses and the effect of the soil was modeled by using springs. The parametric study of the soil was combined with eigenvalue and response spectrum analyses. The response spectrum used for the analysis was the Regulatory Guide 1.60 [5]spectrum shown in Figure 5.

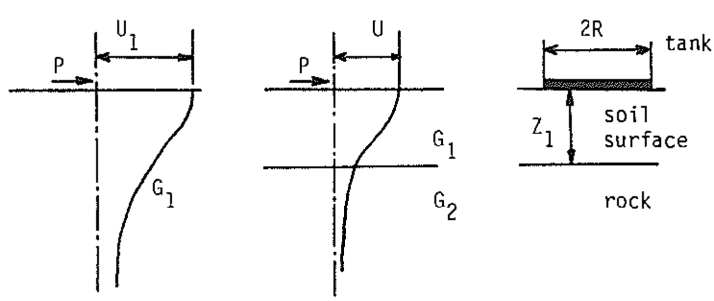
Finally, the effect of soil structure interaction on the natural frequency and response was determined, and the relationship to the CF and typical tank analytical results were obtained. For tanks of dimensions similar to the tank considered in this paper, one can make a general determination of the influence of the soil upon the tank using these tables and curves. In particular the paper identifies the effect of relative stiffness of foundation material to the seismic results of the tank.

2. THEORY OF SOIL STIFFNESS PROPERTIES

There are many studies about the estimation of soil stiffness properties. In this paper, the formulae of Dr. H. Tajimi for general stiffness estimation of layerd soils were applied.

(horizontal stiffness)

From reference 1), the displacement of the surface due to a horizontal load P acting on a semi-infinite elastic medium with shear modulus G_1, is equal to U_1, as shown in Figure (a).



(a) (b) (c)

In Figure (b), the load P acts on layered soil with shear moduli of G_1 and G_2, and produces a displacement U in the same manner as Figure (a) under the assumption of the same stress distribution inside the soil. The displacements U and U_1 can be related by the following equations.

$$U = U_1 \left[1 - F_H(\zeta) + \frac{G_1}{G_2} \cdot F_H(\zeta) \right] \quad \text{-----} \quad (1)$$

where, $\zeta = Z_1/R$ as in Figure (c), and

$$F_H(\zeta) = \frac{1}{2-\nu}\left[\frac{1}{2}\cdot\frac{3+4\zeta^2}{\sqrt{1+\zeta^2}} - 2\zeta + \frac{1-2\nu}{2}\left(\sqrt{1+\zeta^2} - \zeta\right)\right] \quad \text{------------------- (2)}$$

where ν= Poisson's ratio.

To arrive at an equivalent shear modulus to be used in the common soil stiffness formula, we must define the coefficient factor (CF). Setting $\eta = G_1/G_2$, the CF is defined as follows;

$$CF = \sqrt{\frac{U}{U_1}\cdot\frac{1}{\eta}} = \sqrt{\frac{1 - F(\zeta) + \eta\cdot F(\zeta)}{\eta}} \quad \text{---------------------------------- (3)}$$

Using the CF , an equivalent shear modulus Ge can be computed.

$$Ge = G_2/\ (CF)^2 \quad \text{-- (4)}$$

For the horizontal spring's calculation, this equivalent shear modulus may be used in Bycroft's equation for soil spring stiffness as follows;

$$K_H = \frac{32\cdot(1-\nu)\cdot Ge\cdot R}{7-8\nu} \quad \text{--- (5)}$$

The vertical and rotational stiffness are computed by a similar procedure[1].

(vertical stiffness)

$$F_V(\zeta) = \sqrt{1+\zeta^2} - \frac{1}{2(1-\nu)}\left[\frac{\zeta^2}{\sqrt{1+\zeta^2}} + (1-2\nu)\cdot\zeta\right] \quad \text{----------------------- (6)}$$

$$K_V = \frac{4\cdot Ge\cdot R}{1-\nu} \quad \text{(by Timoshenko) --------------------------------------- (7)}$$

(rotational stiffness)

$$F_\theta(\zeta) = \frac{1}{2(1-\nu)}\cdot\left[2\zeta - \frac{3\cdot\zeta^2}{\sqrt{1+\zeta^2}} + \frac{\zeta^4}{(1+\zeta^2)^{1.5}} + 2(1-\nu)\left(\frac{2\zeta^2+1}{\sqrt{1+\zeta^2}} - 2\zeta\right)\right] \text{-- (8)}$$

$$K_\theta = \frac{8\cdot Ge\cdot R^3}{3(1-\nu)} \quad \text{(by Borowicka) -------------------------------------- (9)}$$

For each case the CF and Ge are computed and used in the corresponding spring stiffness equations. Table 1 and Figure 1 show the results of the horizontal and rotational calculations. Figures 2 and 3 show the relations of stiffness ratio to depth and stiffness of the soil surface. These figures show that the relative hardness of the soil layer has more influence on the stiffness ratio than the dimensionless depth of the soil surface layer. Also, when the dimensionless depth ζ is greater than 1.0, the equivalent stiffness is almost constant.

3. COMPUTER ANALYSIS

3.1 MODEL

The authors assumed an aluminum tank, 30' in diameter, 3D' in height and filled with water to 29' high. Figure 4 shows the model of the tank with soil springs.

For the analyses, the SAP IV computer program and Regulatory Guide 1.60 spectrum shown in Figure 5 were used; this spectrum s obtained from RG. 1.60 (β = 7%) and the maximum acceleration was normalized to 0.1g ZPA(Zero Period Acceleration) in this analysis.

Table 2 shows the analytical cases and condition for the parametric survey of the influence of the soil.

Since sloshing effects for this tank geometry are limited, only the impulsive mass of the fluid was considered in the computation for the natural frequency, base shear and overturning moment of the tank. The impulsive water mass distribution was calculated by the formula as follows;

$$\text{mass} = \rho \cdot V_I = \rho \cdot \pi \cdot R^2 \int_{X_1}^{X_2} \left(1 - \frac{\cosh\left(\frac{N(H-X)}{2R}\right)}{\cosh \frac{NH}{2R}} \right) dx \quad \text{--------------------} \quad (10)$$

where, ρ = mass density of water, V_I = impulsive volume, R = tank radius
H = fluid height, X_1, X_2, X = depth in fluid, N = constant depending on ratio of H to R and usually N=6.88

3.2 RESULTS

Table 3 shows the results of the parametric analyses and Figure 6 shows the relationships between the CF and the natural frequency ratio (F_0/F), base shear ratio (Q/Q_0) and overturning moment ratio (M/M_0) where the D subscript indicates the case of base rock with no soil surface layer. The relationships between the 1st and 2nd modes and the CF were obtained. No seismic analysis results are presented here for the variable depth cases because the effect of deeper soil is minor, compared to the effect of stiffer soil on the stiffness ratio.

4. CONCLUSION

The conclusions of these analyses are as follows;

1) The influence of the depth and stiffness of the soil on the response of ground supported vertical tanks can be obtained from the curves and tables, developed in this paper using the formulae of Dr. H. Tajimi.
2) The CF can be correlated with the results of eigenvalue analyses and response spectrum analyses.
3) For typical ground supported tank founded on soils having a shear modulus greater than 3.5×10^6 lb/ft^2 (shear velocity 1D00 ft/sec), explicit introduction of soil structure interaction effects is not warranted.

The authors treated the problem of soil structure interaction in a very simple way and hope the results can be used to expedite the analysis of ground supported vertical tanks on soil foundations.

5. ACKNOWLEDGEMENT

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TABLE 1 COEFFICIENT FACTOR

[HORIZONTAL]

$\frac{Z}{R}(=\zeta)$	$F_H(\zeta)$	ξ=0.05	ξ=0.10	ξ=0.15	ξ=0.20	ξ=0.25	ξ=0.50
0.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
0.1	0.8768	1.8279	1.4522	1.3031	1.2218	1.1703	1.0598
0.2	0.7696	2.3190	1.7532	1.5184	1.3862	1.3005	1.1092
0.3	0.6772	2.6708	1.9762	1.6820	1.5137	1.4030	1.1501
0.4	0.5985	2.9374	2.1479	1.8097	1.6143	1.4848	1.1838
0.5	0.5317	3.1461	2.2836	1.9115	1.6951	1.5508	1.2117
0.6	0.4752	3.3123	2.3923	1.9935	1.7605	1.6045	1.2348
0.7	0.4274	3.4467	2.4806	2.0603	1.8139	1.6486	1.2540
0.8	0.3868	3.5568	2.5532	2.1154	1.8582	1.6851	1.2701
0.9	0.3523	3.6478	2.6133	2.1611	1.8949	1.7155	1.2836
1.0	0.3227	3.7241	2.6638	2.1996	1.9259	1.7412	1.2951
1.25	0.2652	3.8680	2.7592	2.2724	1.9847	1.7901	1.3171
1.5	0.2240	3.9679	2.8256	2.3232	2.0258	1.8243	1.3327
1.75	0.1935	4.0402	2.8738	2.3601	2.0557	1.8492	1.3441
2.0	0.1701	4.0949	2.9102	2.3880	2.0784	1.8681	1.3527

[ROTATIONAL]

$\frac{Z}{R}(=\zeta)$	$F_\theta(\zeta)$	ξ=0.05	ξ=0.10	ξ=0.15	ξ=0.20	ξ=0.25	ξ=0.50
0.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
0.1	0.9568	1.3494	1.1785	1.1157	1.0830	1.0628	1.0214
0.2	0.8956	1.7273	1.3927	1.2616	1.1906	1.1459	1.0509
0.3	0.8207	2.0992	1.6167	1.4199	1.3104	1.2401	1.0860
0.4	0.7379	2.4454	1.8327	1.5765	1.4312	1.3365	1.1234
0.5	0.6532	2.7549	2.0301	1.7220	1.5451	1.4284	1.1605
0.6	0.5712	3.0244	2.2044	1.8520	1.6478	1.5121	1.1953
0.7	0.4952	3.2544	2.3544	1.9648	1.7376	1.5857	1.2267
0.8	0.4268	3.4483	2.4817	2.0611	1.8146	1.6491	1.2543
0.9	0.3668	3.6098	2.5882	2.1420	1.8796	1.7028	1.2780
1.0	0.3148	3.7442	2.6771	2.2097	1.9341	1.7480	1.2982
1.25	0.2160	3.9870	2.8383	2.3330	2.0337	1.8308	1.3357
1.5	0.1507	4.1396	2.9400	2.4110	2.0970	1.8836	1.3599
1.75	0.1076	4.2374	3.0053	2.4611	2.1377	1.9176	1.3756
2.0	0.0787	4.3017	3.0482	2.4941	2.1645	1.9401	1.3861

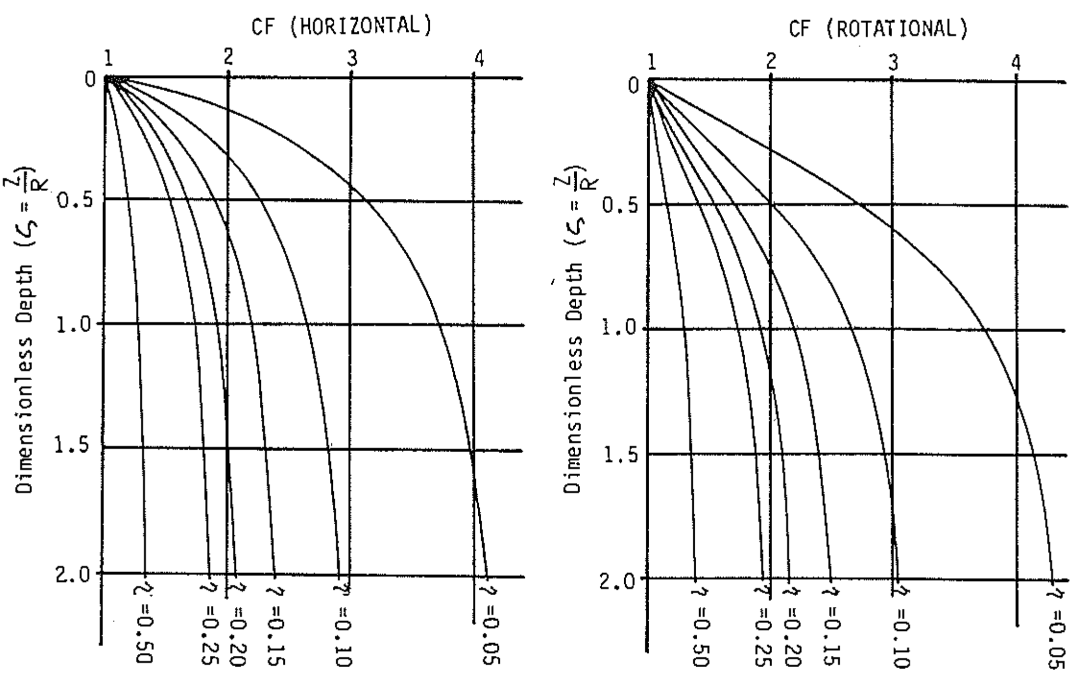


FIGURE 1 COEFFICIENT FACTOR

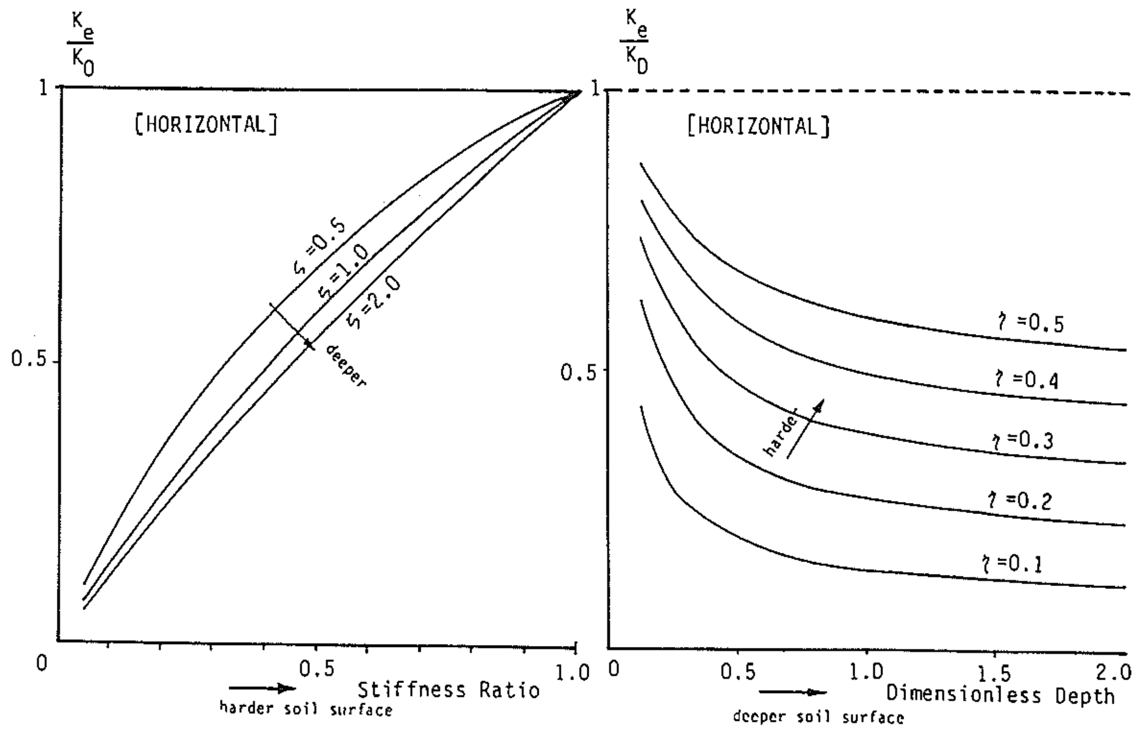


FIGURE 2 RELATION OF STIFFNESS RATIO AND DEPTH & STIFFNESS OF SOIL SURFACE

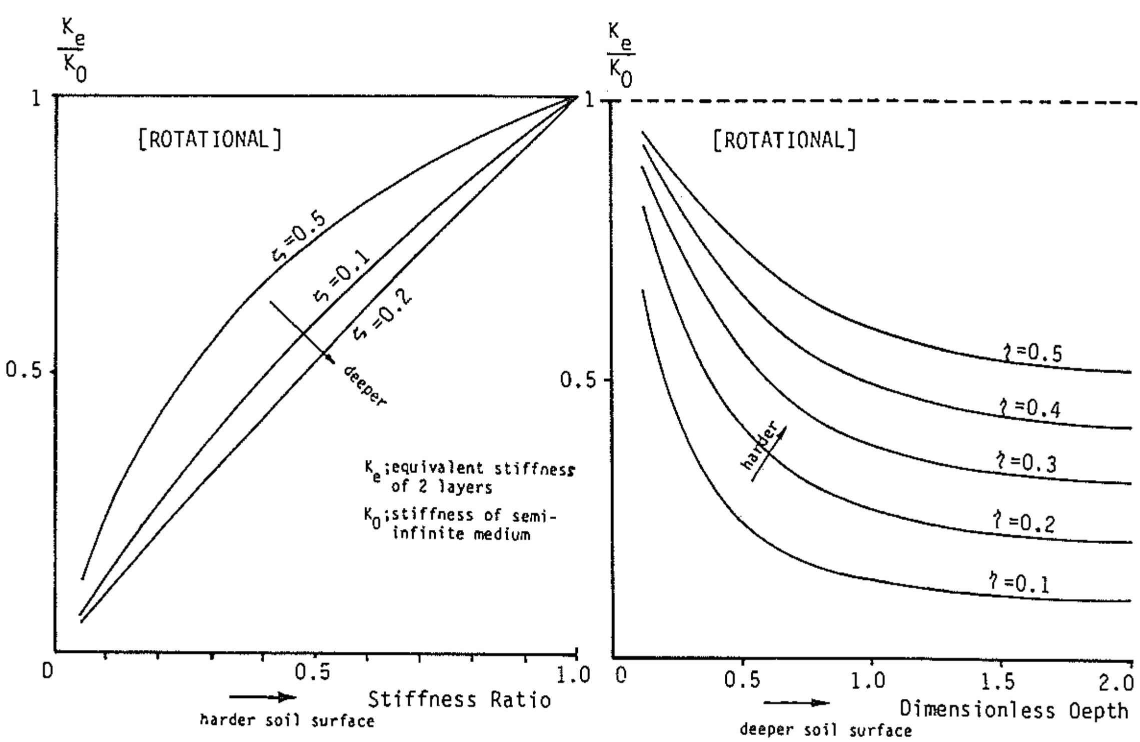
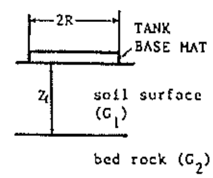


FIGURE 3 RELATION OF STIFFNESS RATIO AND DEPTH & STIFFNESS OF SOIL SURFACE

TABLE 2 ANALYTICAL CASES

	CASE 0	CASE A	CASE B	CASE C	CASE D	CASE E
Depth of soil	semi-infinite bed rock	15 ft (dimensionless ratio ζ =1.0)				
Stiffness of soil	--------	Stiff. ratio η = 0.01	η = 0.02	η = 0.05	η = 0.10	η = 0.20
soil composition	100 X 10^6 (lb/ft^2)	1 X 10^6 100 X 10^6	2 X 10^6 100 X 10^6	5 X 10^6 100 X 10^6	10 X 10^6 100 X 10^6	20 X 10^6 100 X 10^6

	CASE 1	CASE 2 (= CASE D)	CASE 3	CASE 4
DEPTH OF SOIL Z_1	7.5 ft	15 ft	22.5 ft	30 ft
Stiffness of soil	10 X 10^6 lb/ft^2 (Stiffness ratio η = 0.10)			
soil composition	Z_1 100 X 10^6	Z_1 100 X 10^6	Z_1 100 X 10^6	Z_1 100 X 10^6



ζ; depth ratio (Z_1/R)
η; stiff.ratio (G_1/G_2)
R; tank radius 15 ft
G_1,G_2; shear modulus

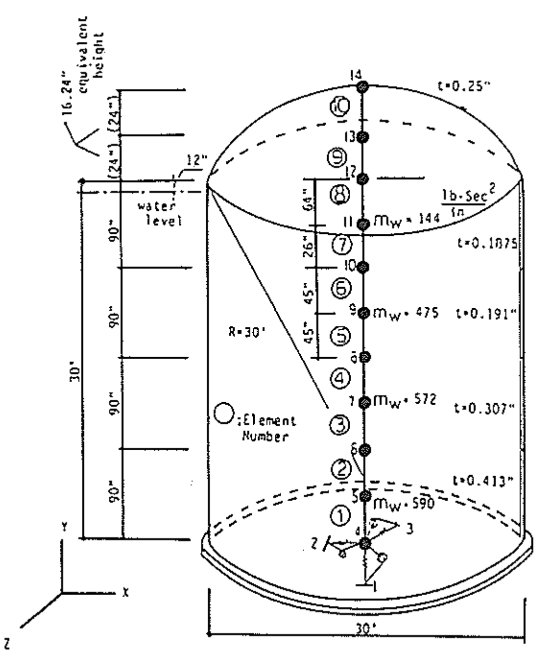


FIGURE 4 ANALYTICAL MODEL OF TANK

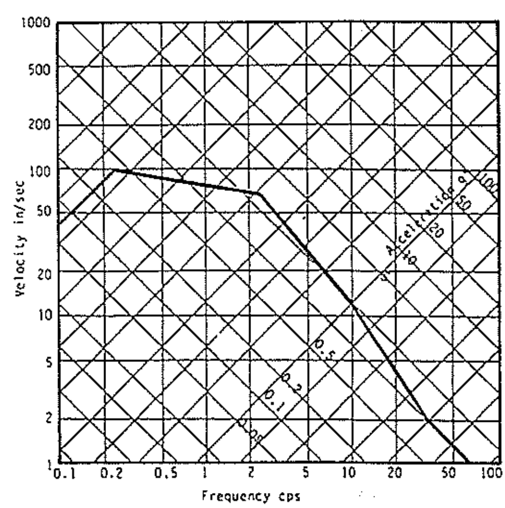


FIGURE 5. SPECTRUM 7% (FROM NRC RG. 1.60)
original is normalized to 1g ZPA

TABLE 3 RESULTS OF SEISMIC ANALYSIS

			CASE 0	CASE A	CASE B	CASE C	CASE D(2)	CASE E
CF		Hori.	1.000	8.249	5.847	3.724	2.664	1.926
		Rota.	1.000	8.297	5.880	3.744	2.677	1.934
Frequency	1st	(Hz)	7.630(F_0)	5.726	6.504	7.143	7.398	7.535
		F_0/F	1.000	1.333	1.173	1.068	1.031	1.013
	2nd	(Hz)	19.94(F_0)	16.26	17.80	19.02	19.49	19.73
		F_0/F	1.000	1.226	1.120	1.048	1.023	1.011
BASE SHEAR(lb)			84320(Q_0)	100300	94700	89040	86680	85380
		Q/Q_0	1.000	1.190	1.123	1.056	1.028	1.013
MOMENT (Klb-in)			16250(M_0)	18040	17400	16790	16520	16370
		M/M_0	1.000	1.110	1.071	1.033	1.017	1.007

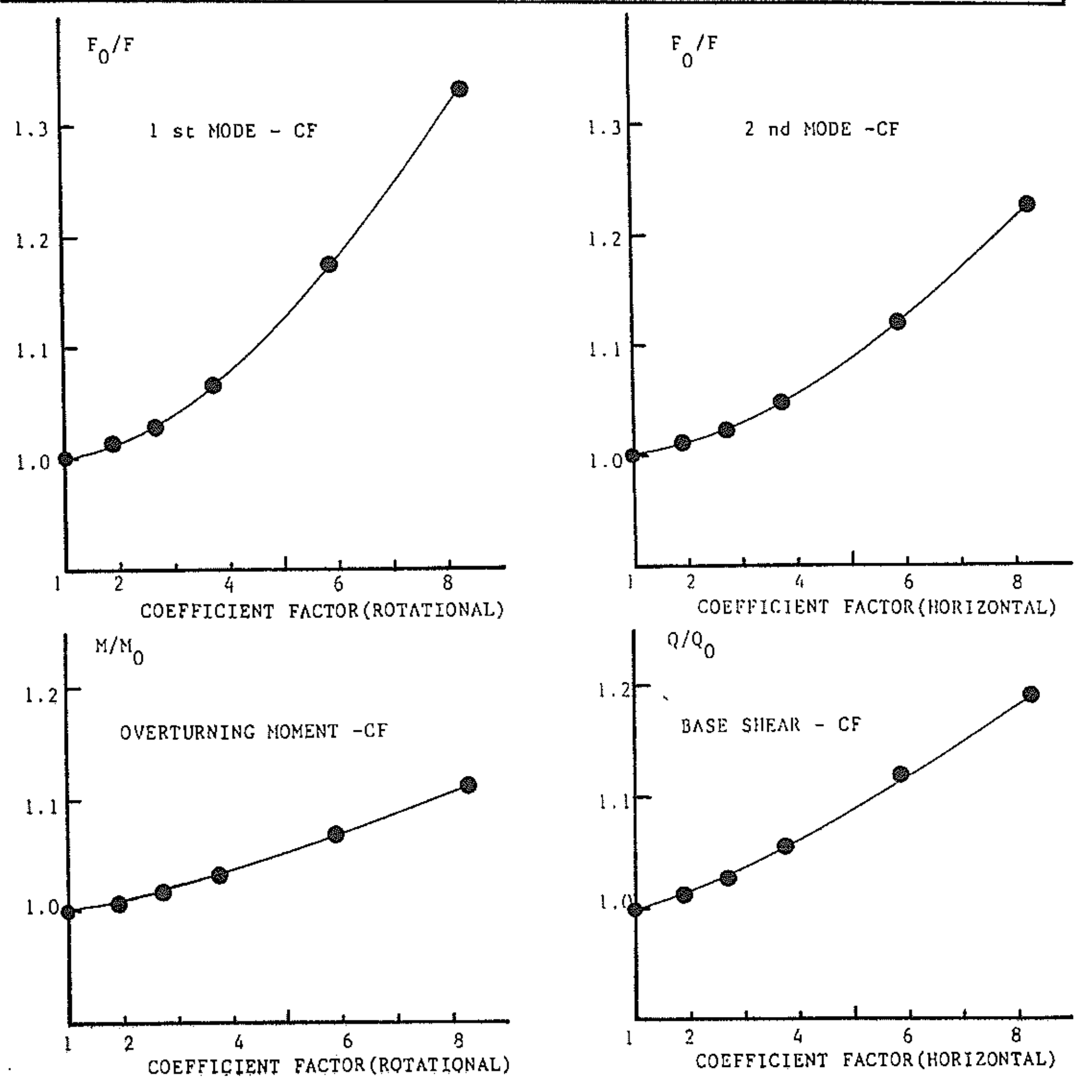


FIGURE 6 RELATION BETWEEN CF AND RESULTS OF ANALYSIS